AIAA 2001-1129

Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications

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39th AIAA Aerospace Sciences Meeting & Exhibit
8-11 January 2001
Reno, NV

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **JAN 2001**		2. REPORT TYPE			3. DATES COVERED **00-00-2001 to 00-00-2001**
4. TITLE AND SUBTITLE **Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,Propulsion Directorate,Wright Patterson AFB,OH,45433**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES **The original document contains color images.**					
14. ABSTRACT **see report**					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES **10**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

DETONATION INITIATION STUDIES AND PERFORMANCE RESULTS FOR PULSED DETONATION ENGINE APPLICATIONS

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Abstract

An in-house computational and experimental program to investigate and develop an air breathing pulse detonation engine (PDE) that uses a practical fuel (kerosene based, fleet-wide use, "JP" type) is currently underway at the Combustion Sciences Branch of the Turbine Engine Division of the Air Force Research Laboratory (AFRL/PRTS). PDE's have the potential of high thrust, low weight, low cost, high scalability, and wide operating range, but several technological hurdles must be overcome before a practical engine can be designed. This research effort involves investigating such critical issues as: detonation initiation and propagation; valving, timing and control; instrumentation and diagnostics; purging, heat transfer, and repetition rate; noise and multi-tube effects; detonation and deflagration to detonation transition modeling; and performance prediction and analysis. An innovative, four-detonation-tube engine design is currently in test and evaluation. Preliminary data are obtained with premixed hydrogen/air as the fuel/oxidizer to demonstrate proof of concept and verify models. Techniques for initiating detonations in hydrogen/air mixtures are developed without the use of oxygen enriched air. An overview of the AFRL/PRTS PDE development research program and hydrogen/air results are presented.

Introduction

Recent renewed interest in pulsed detonation propulsion concepts has prompted a concerted effort being made by the U.S. Air Force (AFRL), U.S. Navy (NRL, ONR, and the Naval Post Graduate School), NASA, and several research contractors (Adroit Systems Inc., Advanced Projects Research, Inc., Pennsylvania State University, Enigmatics, and major engine manufacturers), to develop a low-cost, practical-fueled, pulse detonation engine. Conceptually, a pulse detonation engine (PDE) offers few moving parts, high efficiency, high thrust, low weight, low cost, and ease of scaling. These make the PDE an attractive alternatve to jet turbine engines for small disposable engines. A drawing that illustrates the simplicity of the PDE cycle is provided in Figure 1. The near constant volume heat addition process, along with the lack of a compression cycle, lend to the high efficiency and specific impulse, simplicity, and low-cost of pulse detonation engines. Pulse detonation engines have the potential for operation at speeds ranging from static to hypersonic, with competitive efficiencies, enabling supersonic operation beyond conventional gas turbine engine technology. Currently, no single cycle engine exists which has such a broad range of operability.

Pulsed detonation propulsion research has been funded by AFRL since the early 1990's, but most of the efforts have been performed out-of-house by contractors. In 1997, an AFRL/PRTS (the Combustion Sciences Branch of the Turbine Engine Division, Propulsion Directorate at Wright-Patterson AFB, Ohio) in-house PDE research and development program was created. Principal interests lie in the air-breathing arena; a similar pulsed detonation rocket engine (PDRE) program is being conducted by AFRL/PRSA at Edwards Air Force Base, California.

The in-house PDE program was established in order to make AFRL's unique resources available for the development of this technology. Traditionally, we

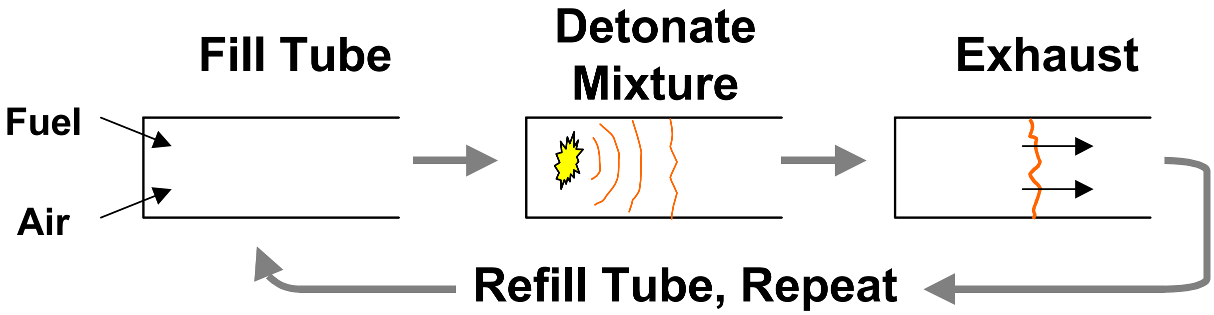


Figure 1. Conceptual pulsed detonation engine cycle.

have used AFRL's advanced computational modeling, diagnostic measurement techniques, and test facilities to work with government agencies and their contractors on the development of advanced combustor concepts. Much of this research was focused on deflagration phenomena while trying to avoid detonations. In order to work with pulsed detonation phenomena, AFRL has set out to develop the facilities, diagnostics, modeling tools, and experience necessary to contribute and provide unique resources for the maturation of pulse detonation technology.

The second motivation of the in-house program was to produce publishable PDE data from which codes and performance predictions can be anchored and/or validated. Currently, there is a great deal of dissension on PDE performance within the community.[1] Detonation physics and detonation engine blow-down are highly sensitive to initial conditions, boundary conditions, and multi-dimensional geometry effects. Most of the available data and models are proprietary and not shared across the community, making it difficult to assess the current status of PDE performance and capability.

For the Air Force, a practical-fueled PDE means JP/air detonation. This requirement creates several technological hurdles that must be overcome in order to field such a PDE. Complex hydrocarbon fuels, and particularly liquid hydrocarbons, are difficult to detonate in air, typically requiring hundreds of kilo-joules to directly initiate a detonation.[2] For this reason, a practically fueled PDE becomes a deflagration to detonation transition (DDT) minimization process since the fuel burned during detonation initiation does not produce thrust efficiently while it is burning at low pressures. Furthermore, since thrust is generated with each detonation cycle, Figure 1, it would be beneficial to raise the operating frequency in order to produce more thrust. Higher operating frequencies also have benefits from an unsteady inlet, nozzle, and noise generation perspective, but create complications in other areas including valving, mixing, shortened residence time requirements, and increased heat loads.

In cooperation with other government organizations performing PDE research and as the developer of one of two government in-house PDE research engines, AFRL/PRTS has established a niche for itself in tackling the above issues. The ONR funded research engine at the Naval Post Graduate School in Monterey, California is directed towards liquid fuel injection, atomization, and mixing[3] and AFRL's engine research is focused on detonation initiation and repetition. While there is crossover in the two programs, we are confident that if we can develop a premixed vapor-fueled/air PDE, the results of the Navy's research will provide the basis for making it work on liquid fuels.

Approach

AFRL's unique resources[4] have been used to develop three areas in which AFRL can contribute to the development of PDE technology. In broad terms, these areas are modeling, facilities and instrumentation, and research hardware development and testing.

AFRL's detonation modeling work is described in more detail elsewhere.[5] Recently this work has been extended to three dimensional calculations and studies of detonation initiation schemes such as the Shelkin spiral calculation in Figure 2. Both calculations employ weak initiation of hydrogen/air mixtures, but the upper frame is a straight channel and the lower contains a two dimensional representation of a Shelkin spiral. The brighter areas in Shelkin spiral calculation indicate that the "hot spots" critical for DDT events are more prevalent with the extra geometry. In the interest of space, further discussion of detonation modeling will not be addressed within this paper.

The Pulsed Combustor/Detonation Engine Research Facility (D-Bay) is capable of supporting up to 60,000 lbf thrust experiments, with integrated remote

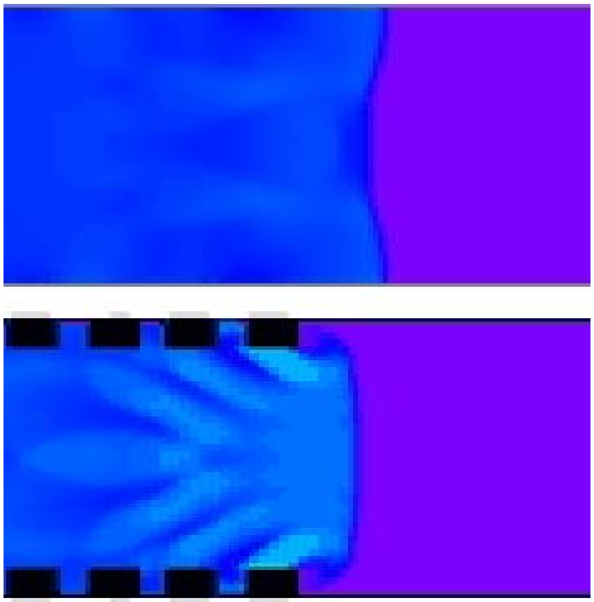


Figure 2. CFD pressure map of DDT event with 2D tube and Shelkin spiral.

control and instrumentation systems. Pulsed thrust measurements from 3 to 1,000+ lbf are accurately made with a damped thrust stand mounted on the existing engine thrust stand. Up to 6 lbm/sec (3 kg/sec) of 100 psi (680 kPa) air is available and high-capacity inlet and exhaust stacks are useful for self-aspirating designs and atmospheric exhaust. A direct connection to a liquid fuel farm via a high-pressure/high-capacity fuel pump retains the facilities ability to feed large-scale 60,000 lbf thrust engines. The facility test stand, damped thrust stand, with an installed research PDE are shown in Figure 3. The damped thrust stand itself sits upon the large capacity static thrust stand and the roll-up door to the exhaust tunnel is visible on the right.

A hardened remote-control room is adjacent to the

Figure 3. Pulsed combustor/detonation engine test stand, damped thrust stand, with installed research PDE.

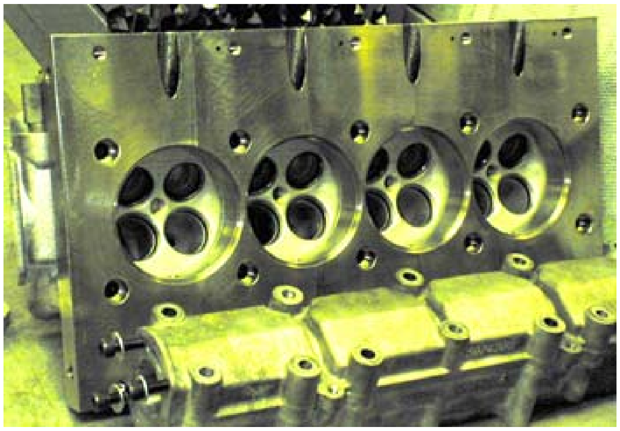
750,000+ ft^3 test cell. A minimum of 2 feet of reinforced concrete is situated between the test cell and personnel during testing. Such precautions are necessary when dealing with the high noise levels associated with PDE operation. Control of all pulsed combustor/detonation engine operations and data acquisition is done via a LabVIEW based interface with duplicate manual emergency shutdown and safety system controls.

Choked flow measurements are employed to accurately regulate and measure oxidizer and fuel flow to pulsed engine experiments. These choke points isolate the measurements from the downstream pressure oscillations of pulsed valves. Each flow system contains a pressure controller, a choked orifice plate or critical flow nozzle, and a surge tank to set and hold a required flow rate even with unsteady combustor valve flows. As long as the flow is choked, flow rate can be varied by changing the pressure and choked area.

In addition to conventional (low Hz and kHz frequency) data acquisition and control systems which include intake, fuel, and purge system instrumentation, the facility is equipped with up to 16 channels of high-frequency data acquisition at up to 5MHz. These may be used for high-frequency pressure transducers, thermocouples, photodiodes, or advanced laser diagnostics. A 1Mhz framing rate digital camera is also available for advanced laser diagnostics and imaging techniques.[6] High frequency pressure transducers and photodiodes are currently installed with plans for digital Schlieren experiments to begin at a later date.

Due to the nature of this facility, testing is not limited to small-scale PDE experiments. Conventional full-scale turbine engine tests are possible making hybrid turbo-PDE's a future research possibility in this facility. It is envisioned that several smaller scale (<1,000 pound thrust) experiments could take place across the test deck or a single large-scale (10,000+ pound thrust) engine test could be performed. As with most of PRTS's test facilities, easy swap-out of test hardware is expected and accounted for in the initial test-facility design.

Due to the critical timing issues in pulsed detonation engine operations, the high frequency valving tends to be both expensive and highly constrained. During the design of a research PDE, many options were considered that were either too expensive, had severe limitations in operating range, or both. The research engine design selected is based upon valving found in a General Motors Quad 4, Dual Overhead Cam (DOHC) cylinder head commonly used in the Pontiac Grand Am automobile. This PDE design



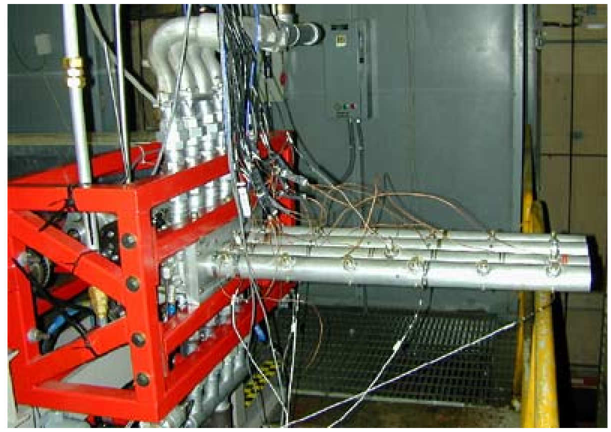


Figure 4. Second generation "Quad 4" based PDE during assembly (left) and as installed.

has an extremely broad operating range and configuration, with up to four detonation tubes operating at up to 100 Hz each. The engine has proven reliability and durability, although the loss of the first generation engine design did occur due to fatigue in the tube mount area after approximately 200 hours of hot time.[7] The head and tube mount systems have been redesigned to permit higher frequency operation, quick valve system and detonator tube configuration change-outs, and eliminate the areas where fatigue became a problem. The second generation engine is shown in Figure 4 during assembly and as installed in the damped thrust stand.

The operating conditions of PDE's are very similar to internal combustion engines and many of the components can be shared. By driving the overhead cams with an electric motor, the four valves in each of the four cylinders can be made to operate at between 0.5 and 50 Hz. With minor modifications, the frequency limit can be increased to 100 Hz for an aggregate maximum frequency of 400 Hz. Currently, several different detonator tube configurations are available including single 2" (50 mm) diameter by 3' (900 mm) tube, single 3.5" (90 mm) diameter by 3' (910 mm) tube, and multiple tube versions of each of the previous configurations. Provisions for lubrication, cooling, ignition, and fuel delivery are integral to the cylinder head/intake manifold assembly. The electric valve-train drive motor, which is grossly oversized but a readily available component, is clearly visible on the left side of the frame in Figure 3, along with the valve train drive parts.

The two intake valves in each cylinder, visible in Figure 5, are used to feed premixed air and fuel into detonation tubes, which are attached to an adapter plate secured by the head bolts. In the current configuration, the head and detonation tubes are installed horizontally, and the intake valves are the upper pair. Cold air flows through the exhaust valves in reverse as a purge gas to buffer hot products from igniting the next incoming charge and to convectively cool the inside of the detonation tube walls. The extra exhaust valve or valves in this four-valve-per-cylinder design could also be used for an axial predetonator or additional combustion air if necessary.

Somewhat uniquely, this PDE is operated premixed, minimizing mixing and stratification issues. The large pop-off valves and check valves visible in Figure 3 are some of the precautions used to prevent catastrophic failure in the event of an engine backfire through the premixed intake section. Up to four detonation tubes can be run at 90 degrees out of phase, with various diameters ranging up to ~3.5 inches (85mm). The main combustion air and purge air lines contain ball valves for each detonation tube feed system so that the engine can be run with one tube, two tubes 180 degrees out of phase, or all four tubes. A rotary

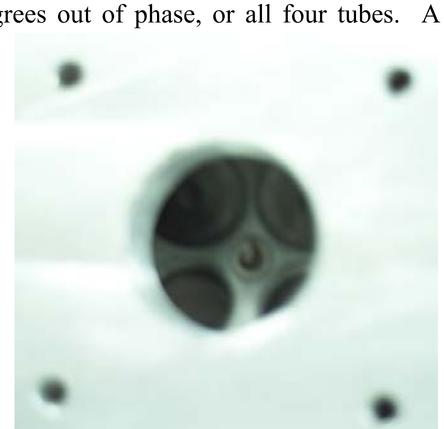


Figure 5. Research 'Quad 4' PDE detonation tube adapter plate with visible intake (upper) valve pair, purge air (lower) valve pair, and conventional spark igniter.

position sensor is adapted to the intake camshaft to provide both an index of the valve timing sequence and the relative position of the valves. This signal serves as the master timing signal for the ignition and data acquisition systems.

An eight-channel igniter/fuel injection control box is triggered off the rotary position sensor. Separate control of each detonation tubes igniter and/or fuel injector can be accomplished with this system, although currently vapor fuels are premixed with the combustion air via a separate critical flow nozzle and flow control system. Do to the high noise levels associated with PDE testing, all controls and data acquisition are performed remotely from an isolated control room. All of the control systems and data acquisition systems are LabVIEW based and integrated into one 'virtual instrument' with back-up manual shutdown and safety systems. This virtual control panel is extremely flexible and can control all aspects of the PDE's operation including: lubrication, operating valve drive motor speed, fuel flow, main combustion air flow, purge air flow, timing, ignition delays, and automatic shutdown in the event of a critical system failure. By changing the position of a few manual ball valves and pushing a few switches in the virtual control system, the engine configuration can be switched from one tube operating to four tubes in a matter of minutes.

The engine is to be used for performance prediction validations and serve as a test-bed for research of detonation initiation and DDT minimization, heat transfer, noise levels, pulsed ejector concepts, and multi-tube interactions. Initial testing and proof-of-concept is being done with hydrogen as the fuel due to the increased detonability versus practical liquid hydrocarbon fuels. A vapor propane fuel system has also been constructed in order to work with a complex-hydrocarbon that detonates much like kerosene based JP type fuels. This will eliminate the atomization and mixing of liquid fuel complications that increase the difficulty of practical PDE design and allow us to focus on detonation initiation and high frequency operation. As mentioned previously, ONR funded research is tackling the difficult problems of liquid fuel atomization and mixing for PDE applications.[3,8] Recently, active cooling has been implemented along with expanded fuel systems so that indefinite run times are possible. Further details on the research facility and engine are available elsewhere.[9]

Results and Discussion

Cold flow testing of the systems began in early 1999, with the first hot firing on 9 September. This

Figure 6. In-house research 'Quad-4' PDE, success on first attempt, 9 September, 1999: 91 second operation at 8Hz, single 2" diameter by 3' long tube, stoichiometric H_2/air, conventional ignition.

initial test was done at low fuel flow conditions to minimize the amount of hydrogen in the test cell in event of a failure. The first test was done with fully instrumented intake and purge systems, detonation tube surface temperature thermocouples, four high frequency pressure transducers along the length of the tube, damped thrust, and two black & white video cameras. An image extracted from one of the video cameras is shown in Figure 6.

The initial testing produced very good qualitative results, with four runs of up to 91 seconds duration. These runs, which were un-cooled, were cut short because the tube surface thermocouples were epoxy mounted and the epoxy melted. The thermocouples have since been re-affixed more robustly. The sharp 'CRACK' sound and flash of the exhaust were qualitative indicators of detonations which contrasted with the softer 'wumpff' sound and flame visible out the back when the engine deflagrated due to off-stoichiometry conditions.

Although data has now been obtained with propane/air, the results presented herein will focus on hydrogen/air operation. Results presented were obtained with a single aluminum 2.0" (50.8mm) ID tube that was 36" (915mm) long. Conventional weak initiation was employed at the head end (via the spark plugs visible in Figures 4 and 5) with a 3.5 msec ignition delay. The fuel/oxidizer mixture was stoichiometric and premixed hydrogen/air with a 50% clean air purge fill ratio. The above operating parameters and an operating frequency of 16 Hz applies to all data herein unless otherwise stated.

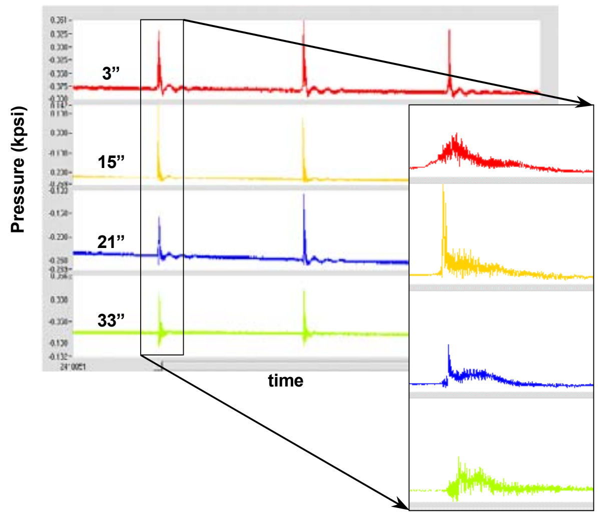


Figure 7. High frequency pressure traces from in-house PDE engine. Measurement locations at 3, 15, 21, 33” axial distances from head, ~200 msec duration shown.

Initially it was found that the detonation did not transition from deflagration until near the end of the detonation tubes. The addition of a Shelkin or shocking spiral produced much faster transitions and higher thrust levels. A 3/16” wire diameter spiral with a ~1.8” pitch was placed in the first 12” of the detonation tubes. This spiral produced overdriven detonations by the 9” axial location. High frequency pressure transducer measurements, as seen in Figure 7, indicate measured wave speeds of 1959 m/sec. Further experimental verification of detonation wave speeds was provided by photodiode measurements shown in Figure 8 with a derived wave speed of 1959 m/sec. These results are in excellent agreement with the stoichiometric hydrogen/air wave speed of 1968 m/sec published elsewhere.[10]

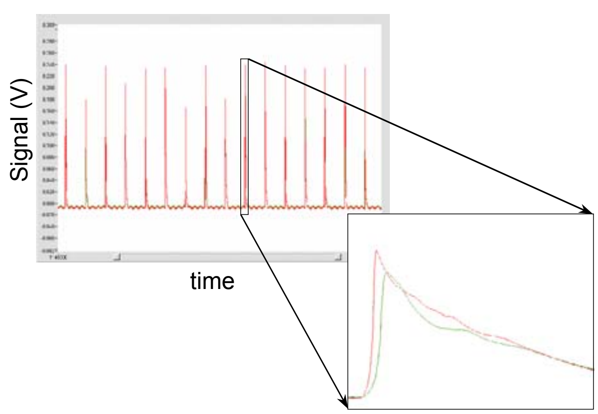


Figure 8. Photodiode results at 27 and 33” locations.

Since the initial single tube tests, the engine has been run in multi-tube mode, demonstrating both two-tube operation 180° out of phase and four tube operation 90° out of phase. A wide variety of frequencies have also been demonstrated along with operation of the tubes using partial fills.

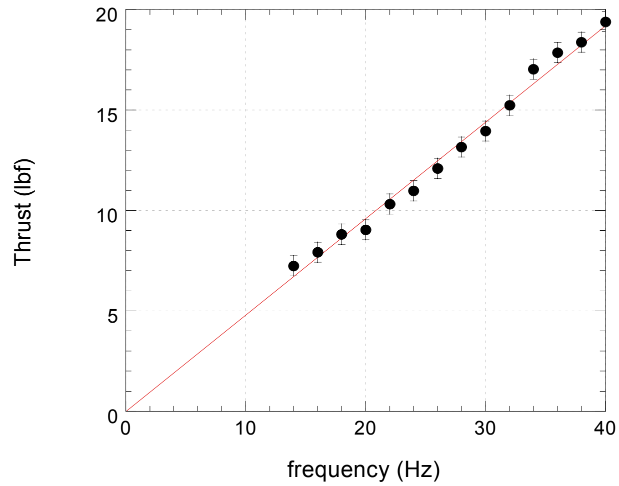


Figure. 9. Thrust versus frequency.

PDE’s are highly scalable, as demonstrated in Figure 9. The thrust is observed to increase linearly with frequency, with the engine making no thrust when not operating as expected. This data also demonstrates the accuracy of the thrust measurements, as the error bars are +/- 0.5 lbf (+/- 2.2 N). Such thrust measurements have been demonstrated with the current system down to 3 lbf (13 N) but the accuracy and thrust range can be varied with configuration changes.

The impact of ignition delay can be assessed with

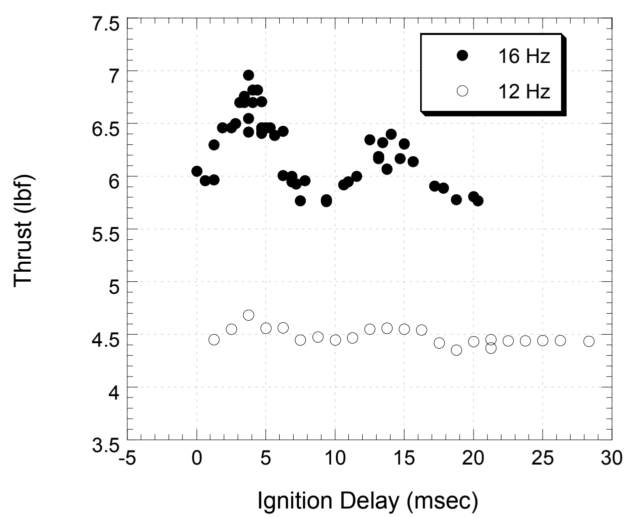


Figure. 10. Thrust versus ignition delay.

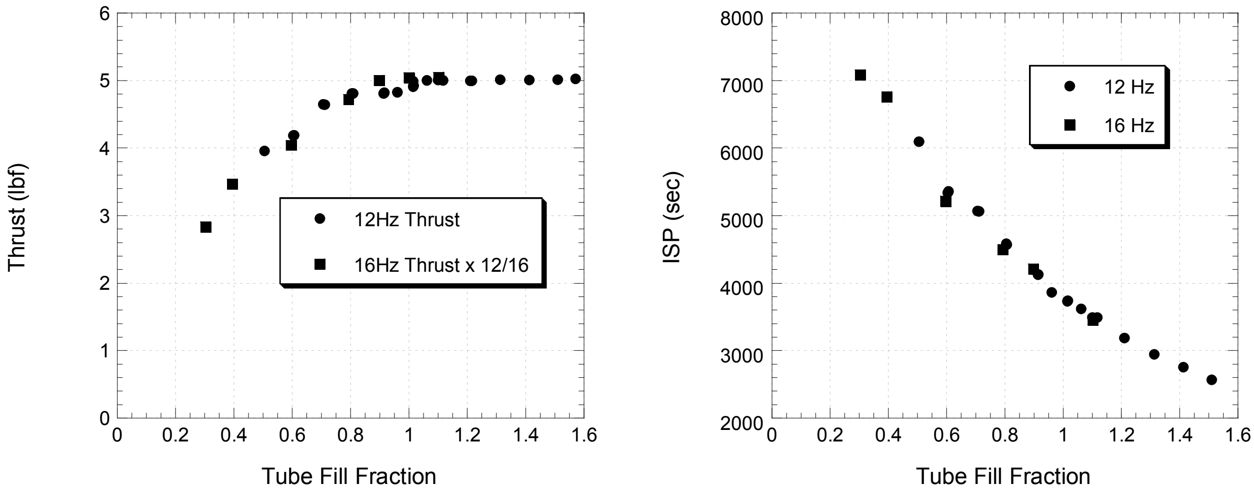


Figure 11. Thrust (left) and fuel specific (right) impulse versus tube fill fraction.

the data in Figure 10. The plot of thrust versus ignition delay contains data for two different frequencies. Ignition delay here is defined as the time in milliseconds between the intake valve closing completely and spark plug firing. Obviously, with premixed operation, negative ignition delays are to be avoided as they can result in combustion before the intake valves are closed with consequent backfiring through the intake system. It was found that premixed operation reduces the sensitivity of performance to ignition delay, as some PDE systems have been observed to detonate only within a narrow ignition delay window of only a few milliseconds. However, certain trends are apparent at both frequencies presented.

The ignition delay is observed to produce high and low spots. Because detonability is sensitive to changes in pressure, the initial low spot is surmised to be a result of attempting to initiate a detonation in the expansion resulting from the closing of the intake valve. The peaks at 3.5 msec ignition delay are believed to occur due to the presence of the subsequent compression wave. These behaviors are then observed to repeat at periods corresponding to the acoustic length of the detonator tube.

PDE scalability is also accomplished via variation of the volume of the tube filled with detonable mixture. Via volumetric flow control, the tube fill fraction was varied as shown in Figure 11. Results are shown for two frequencies to cover a range of fill fractions while remaining within the limits of a single choked-orifice volumetric flow control range. Thrust measurements on the left are scaled by frequency to 12 Hz. Due to the linear relationship of thrust and frequency, Figure 9, the differing frequencies collapse on one another when scaled by frequency. Further confirmation of this phenomenon is evident in the fuel specific impulse plot on the right in Figure 11. Here frequency is accounted for when dividing by the fuel flow and no other frequency scaling is required.

At a fill fraction of 1.0, the entire tube is filled with fresh reactants for each cycle. At fill fractions less than 1.0, only part of the tube is filled with fresh reactants with the remainder occupied by either a purge cycle or hot expanded products from the previous cycle. At fill fractions greater than 1.0, the entire tube is filled with the excess detonable mixture presumably forming a free cloud at the tube exit. Thrust versus tube fill fraction is plotted on the left in Figure 11. The thrust is observed to increase with tube fill fraction until abruptly leveling out at a fill fraction of 1.0. Since reactants detonating outside the tube are unconfined, they do not produce any thrust as shown for the fill fractions greater than 1.0. Note that even at tube fills corresponding to only 30%, more than half the peak thrust is still obtained. This results in up to double the efficiency as shown by the increased fuel specific impulse at fill fractions less than 1.0. This trend, which has been confirmed by Li, Kailasanath, and Patnaik using CFD,[11] is a result of longer blow down times produced by the increased acoustic relaxation length for partial tube fills. Effectively, purge air or previous cycle products are pumped by the detonation, resulting in the same higher mass/lower delta-velocity efficiency gains found in modern high-bypass turbofans. The remarkable efficiency gains are partly due to the increased efficiency of shock coupling in the PDE as compared to the viscous coupling in the turbofan.

In addition to the effects of frequency, ignition delay, and fill fraction, the impact of stoichiometry was

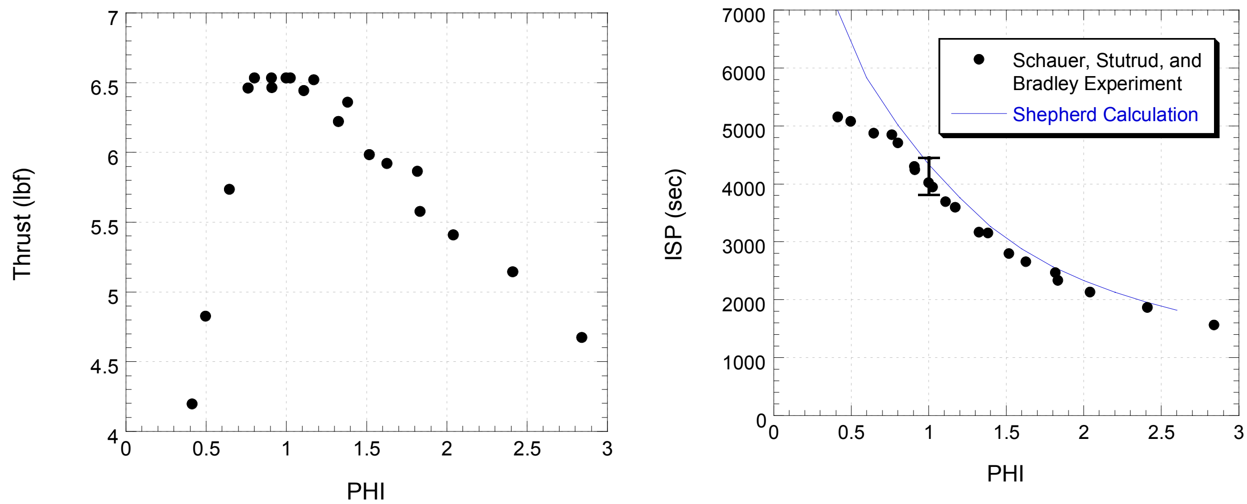


Figure. 12. Thrust and fuel specific impulse versus stoichiometry.

also examined as shown in Figure 12. Thrust on the left and fuel specific impulse on the right are plotted versus a wide range of stoichiometries. As expected from detonability data,[2] a stable region is observed at stoichiometries near 1.0. At fuel rich conditions, both the detonability and thrust are observed to fall off gradually with increasing fuel to air ratio. The detonability and thrust fall off more quickly on the fuel lean side of the stoichiometry curve. As with partial tube fills above, more than half the thrust is observed to occur even with only half the stoichiometric fuel to air ratio. This results in a higher efficiency for lean operation as confirmed on the specific impulse plot.

The current experiments are graphed in Figure 12 along with Joe Shepherd's analytical calculations[12] with excellent agreement across a wide range of equivalence ratios. The experimental error bar shown represents the variation in thrust possible by changes in ignition timing alone, Figure 10, as the data was collected with a constant ignition delay. Shepherd's results do not consider deflagration to detonation processes. The fall off in specific impulse observed experimentally for equivalence ratios less than 0.75 can be attributed to the rapid growth in DDT distance as the cell size gets much larger than the detonation tube size.

Summary and Conclusions

Pulse detonation engines are an extremely promising alternative to small, disposable-jet turbine engines. The Air Force Research Laboratory has supported PDE research for some time, and an in-house program of the Combustion Sciences Branch of the Turbine Engine Division at Wright-Patterson AFB has been established to produce shareable benchmark performance data. In addition, the in-house program has been used to harness AFRL's unique resources in order to contribute to the development of pulsed detonation propulsion technology in the form of modeling, facility, and research components.

It is expected that the deflagration to detonation transition modeling can be used as a tool in the development and design of a practical-fueled detonation initiator. The pulsed combustor/detonation engine test facility has been developed as a cost-effective test resource that meets many of the unique needs required for PDE testing. The remote controls and high frequency data-acquisition systems have been assembled to provide test support for researchers working in collaboration with AFRL. The facility can handle everything from bench scale experiments from academia to full-scale hybrid engine concepts from engine manufacturers. Moreover, it is hoped that researchers will take advantage of this national resource.

A research PDE was successfully designed, built, and operated under the in-house program using an innovative valve system based upon the "Quad-4", a 16 valve, four cylinder automobile engine from General Motors. The resulting engine is capable of a broad range of frequencies and configurations with up to four detonation tubes. Data from the engine is being published with the intent of providing non-proprietary PDE data against which performance codes and predictions can be benchmarked. The "Quad-4" PDE serves as a research tool and test-bed for detonation initiation concepts, high frequency operation, heat transfer studies, multi-tube detonation engine operation, and pulsed ejector research. The engine, which was

operated successfully for the first time in the fall of 1999, demonstrates the affordability and ease of scalability of PDE technology. The first generation engine operated for over 16 million cycles and approximately 200 hours of detonations before components failed due to fatigue. The engine demonstrated that PDE's can operate for extended durations even with low cost materials and designs. A second-generation engine design has been completed to replace the failed engine with numerous design improvements to durability and capability.

Hydrogen/air data have been presented on the effects of frequency, ignition delay, fill fraction, and fuel/air equivilance ratio. The resultant findings provide insight for scaling thrust and improving efficiency of PDE hardware. Data sets are available for collaborative studies, including flow conditions and heat transfer data not published herein. Additional data on propane/air detonations are available for qualified researchers.

There is much work to be done in developing valving, detonation initiators, noise suppression techniques, thermal protection systems, intake and exhaust nozzles, and control systems before a JP/air fueled PDE becomes practical. AFRL/PRTS would like to invite the community to consider AFRL resources for further PDE research. With high quality modeling, research facilities, and an in-house PDE engine, AFRL can work with other organizations and contractors, as done in the past with turbine engine technology, to maturate and transition PDE technology to the field.

Acknowledgements

Special appreciation must be expressed to the technicians and support personnel, both in-house government employees and on-site contractors who made this work possible, particularly Dwight Fox (ISSI) who helped build much of the research PDE engine and Walt Balster (ISSI) who recently joined us as a facility technician. Dr. Vish Katta and Dr. L.P. Chin have performed their usual miracles on the modeling side and are gratefully acknowledged for their contributions to this program. We also wish to acknowledge the technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS).

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